

An Investigation of Differential Deposition for Figure Corrections in Full-Shell Grazing-Incidence X-Ray Optics

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ABSTRACT

We are investigating differential deposition as a way of correcting small figure errors inside full-shell grazing-incidence x-ray optics. The optics in our study are fabricated using the electroformed-nickel-replication technique, and the figure errors arise from fabrication errors in the mandrel, from which the shells are replicated, as well as errors induced during the electroforming process. Combined, these give sub-micron-scale figure deviations which limit the angular resolution of the optics to ~ 10 arcsec.

Sub-micron figure errors can be corrected by selectively depositing (physical vapor deposition) material inside the shell. The requirements for this filler material are that it must not degrade the ultra-smooth surface finish necessary for efficient x-ray reflection (~ 5 Å rms), and must not be highly stressed. In addition, a technique must be found to produce well controlled and defined beams within highly constrained geometries, as some of our mirror shells are less than 3 cm in diameter.

We report on our efforts to date to implement this technique.

Keywords: X-ray optics, Differential deposition

1. BACKGROUND

X-ray optics have revolutionized x-ray astronomy, and the best observatories to date have arcsecond-level angular resolutions. However, these levels of performance are obtained with relatively thick (cm-scale) mirror shells that are meticulously figured and polished (see for example the Chandra observatory [1]), and these are very expensive to produce and to place on orbit. Other approaches, such as electroformed-nickel replication [2] trade angular resolution for ease of fabrication and thus produce much less costly thin-shell optics (sub-mm scale), which can be nested to give much larger collecting areas but with significantly poorer imaging performance. Future x-ray astronomy missions demand, however, both high angular resolution and large effective areas.

The principal factor limiting performance in thin-shell electroformed optics is axial figure errors. These arise from both fabrication errors in the mandrel, from which the shells are replicated, and from the electroforming process, where small amounts of plating stress cause deformation in the figure of the resulting free-standing mirror shell. As shells are made ever thinner, the electroforming effects become more significant. While mandrel figures can be improved with precision fabrication, the plating bath stresses are dependant on bath chemistry, electric field configuration and fluid flow, and these are hard to control at the very low levels necessary for optics production. To date, the best electroformed thin shells have angular resolutions more than an order of magnitude worse than the optics on the Chandra x-ray observatory.

The purpose of this study is to investigate a differential deposition technique which can potentially reduce errors in the axial figure profile of electroformed (and other thin shell) optics. This technique has been successfully

implemented in the past for refiguring x-ray optics to different profiles [3,4] but has not to date been implemented for correcting full-shell x-ray mirrors.

For this investigation we have utilized Wolter-type grazing incidence X-ray optics. Wolter optical designs developed by Hans Wolter in 1952 use a combination of hyperbolic, parabolic and/or elliptical mirrors to perform X-ray imaging [5]. These combinations improve off-axis response and the parabolic+hyperbolic combination in particular has been used extensively in X-ray astronomy [6].

For proof of concept we have utilized very small Wolter optics that we have been developing, not for x-ray astronomy but for small animal radionuclide imaging. These small-surface-area optics allow figure corrections to be applied within reasonably short coating run times.

2. DEPOSITION TECHNIQUE

Physical vapor deposition provides a means of selectively coating the inside of a mirror shell to fill in figure imperfections. Typical deposition rates permit 100's of nanometers to be applied on reasonably short timescales and sputtering in particular allows significant coating thickness without degrading the optical surface. The space available inside a mirror shell, particularly those intended for hard x-ray energies where graze angles are quite shallow, can be quite small, and so this makes it difficult to use conventional sputtering approaches such as DC magnetron. We have instead opted for an RF system, where material is sputtered from a cathode rod inserted down the middle of the mirror shell. The use of a suitable mask, then permits the generation of a fan beam with accurately known profile which can be used to coat selected area inside the mirror shell. This arrangement is shown schematically in Figure 1. A static mask surrounding the target filler rod is used to generate a plasma, and the resulting beam of sputtered material, exiting through a slot in the center of the mask, is used to selectively coat regions of an x-ray optic which is translated across it. Thus varying thicknesses of material are deposited along the length of the shell to correct its axial figure. The mask has a slit of finite width to limit the spatial extent of the deposition. The slit-width is chosen to correct specific spatial scale deviations from the desired figure. The optic rotates around the mask, to ensure uniformity and is translated linearly over the slit of the mask with a predefined variable velocity profile derived from shell figure metrology. Figure 2 depicts the deposition process, as the optic is moved over the mask to give the desired axial coating profile.

The RF sputtering system is filled with an inert gas such as Argon or Xenon at few mTorr of pressure and operates at a frequency of 13.56 MHz. The application of this RF to the target rod generates a local plasma in which positively charged inert gas ions hit the target with high energy, and this results in sputtering of atoms from the target surface. Some of the sputtered target material passes through a slit in the mask to deposit on the optic as described above.

Figure 3 shows the experimental setup used. Visible in the right figure (a) is the interior of the sputtering chamber showing the target rod, the mask, and the mirror shell mounted in collet that rotates and translates it. Figure 3b shows a mask with a 5 mm slit.

3. APPLICATION

To develop and demonstrate the differential coating technique we have utilized miniature optics designed for small animal radionuclide imaging (Figure 4). These are being fabricated at MSFC and will be used for noninvasive radionuclide imaging to perform functional and metabolic assessment in small animals. They have a combination of confocal hyperbolic and elliptical segments to perform on-axis imaging. Figure 5 gives a cross sectional view of the optical layout with the object (source of X-ray emission) located at the left focal point of the hyperbola and the image at the right focal point of the ellipse.

Small optics such as these are a challenge to fabricate. Typically, an electroformed mirror shell will have poorer figure at its ends, due to stress concentrations, and in these very short shells (5-6 cm) this effect dominates. Thus while 10-20 arcsec resolutions can typically be expected from larger electroformed optics, these shells typically perform nearer the arcminute level. The figure deviations responsible for this are, however, appropriate for the

85 differential deposition correction technique. With this, we hope to improve the figures to give 10's of microns
86 spatial resolution, which are desirable for many (medical and non-medical) applications. This corresponds to an
87 angular resolution of below 10 arcsec.

88 4. SIMULATIONS

89 Extensive simulations have been performed to model the effects of the coating and thus to develop strategies for
90 optimal figure corrections. These simulations model the beam profile and describe the motion profile of the mask
91 necessary to give a desired overall coating profile. In practice the mask is stepper-motor controlled and so the
92 program determines the dwell time at each position necessary for the correct figure.

93 Obviously the coating beam profile is defined by the slit width in the mask and the mask to shell distance. The latter
94 is typically kept at a minimum to reduce the wings of the profile. Fine slit widths enable high-frequency components
95 to be filled in but are obviously very inefficient for coating broad features. Thus there is an optimum process, where
96 a coarse mask is used to correct large figure deviations, followed by successively finer masks for the shorter scale,
97 typically lower amplitude, figure errors. Such the process, obtained by stepping the optic across the mask to add up
98 the desired profile after normalizing the dwell time (i.e. the deposition quantity) at each location, can be simulated
99 based on the material deposition profiles for each mask size.

100 Actual figure correction on an optic depends on metrology to determine the optic's current figure and then
101 subtraction from a desired figure to obtain a 'hit map' of the required deposit. To achieve this deposit, several slit
102 widths are necessary, with their selection is dependent upon the spatial frequency of the deviation to be corrected.
103 Figure 6 shows simulation results comparing the profiles on the hyperbola and ellipse before and after differential
104 deposition correction done with a series of slit sizes of 5mm, 2mm and 1mm successively.

105 5. EXPERIMENTAL RESULTS

106 The choice of filler material and deposition parameters is very important. A suitable deposited material must have
107 low surface roughness even for thick deposits, must have low stress, must adhere to the underlying mirror
108 substrate and must have a reasonably large deposition rate. For these tests 2-mm-thick D283 glass which had an
109 initial surface roughness of 2 Å rms was used as a coating substrate. We used various deposition materials including
110 platinum, tungsten, and nickel, which were preselected based on information regarding their deposition behavior.
111 We varied such parameters as sputter-gas type (argon and xenon) and pressure as well as the RF sputtering power,
112 and measured the resulting samples on a WYKO optical profilometer to gauge surface roughness and on a Talysurf
113 stylus profilometer to gauge deposition rates. We performed tape tests on suitable samples to gauge adhesion. The
114 results of these tests are given in Table 1.

115 Based on these results we have selected nickel as the best coating material, used with xenon sputtering gas at a
116 pressure of 15 mTorr. This combination gave a high deposition rate, a very low surface roughness and robust
117 adhesion to the underlying nickel mirror substrate.

118 With optimum coating parameters selected, we have verified the beam profiles and obtained rates for a series of
119 masks fabricated with different slit sizes. We find these to be very close to those profiles predicted by our
120 simulation. We have recently commenced coatings on actual mirror shells, and are optimizing metrology to obtain
121 reliable data for figure correction. Precise figure measurements on small-diameter shells is challenging as
122 conventional optical systems are too bulky for inside measurements. We are currently modifying an optical system
123 to miniaturize the scanning head. In the meantime we are using a mechanical stylus profilometer, and averaging
124 many measurements to obtain good statistics. Figure 7 shows a recent early attempt at correcting the ellipse
125 segment of our medical optic with a broad beam.

126 At the time of writing we are ready to start a full shell correction. We have selected a suitable candidate and are
127 performing detailed metrology. The shell will then be tested in x-rays and compared with a prediction based on the
128 shell profile metrology. A full correction will then be applied and the metrology and x-ray tests repeated. It is

129 anticipated that a significant improvement in performance will be obtained. Assuming this is the case future plans
130 include adapting the technique to larger optics suitable for x-ray astronomy.

131 6. CONCLUSION

132 We are developing a differential coating technique for figure corrections in full shell optics. We have assembled a
133 suitable system, based on RF sputtering, and have selected suitable coating parameters and a coating material to
134 enable substantial deposits at useful rates, having good surface finish and good adhesion. We have performed some
135 preliminary tests to check out the system and are now ready to perform our first full shell correction.

136 REFERENCES

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- [1] <http://www.chandra.harvard.edu>
 - [2] <http://www.esa.int/esapub/bulletin/bullet89/chamb89.htm>
 - [3] S. Handa, H. Mimura, H. Yumoto, T. Kimura, S. Matsuyama, Y. Sano, K. Yamauchi, Surface and Interface Analysis, 40 (2008) 1019-1022.
 - [4] G.E. Ice, J.-S. Chung, J.Z. Tischler, A. Lunt, L. Assoufid, Rev. Sci. Instr., 71(7) (2000) 2635-2639.
 - [5] H. Wolter, Ann Physik, 10 (1952) 94-114.
 - [6] R. Giacconi, N. F. Harmon, R. F. Lacey, Z. Szilagyi, J. Opt. Soc. Amer., 55, (1965) 345-347.

Figure Captions

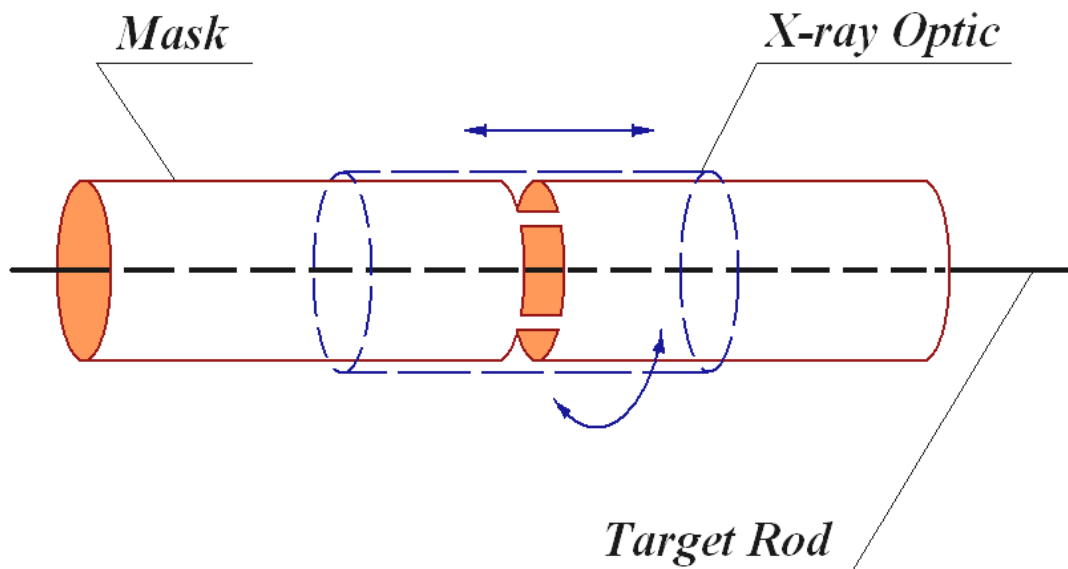


Figure 1: Target rod, mask and optic positioned concentrically. The optic is rotated around the mask while it is translated linearly with variable velocity to give the desired coating profile.

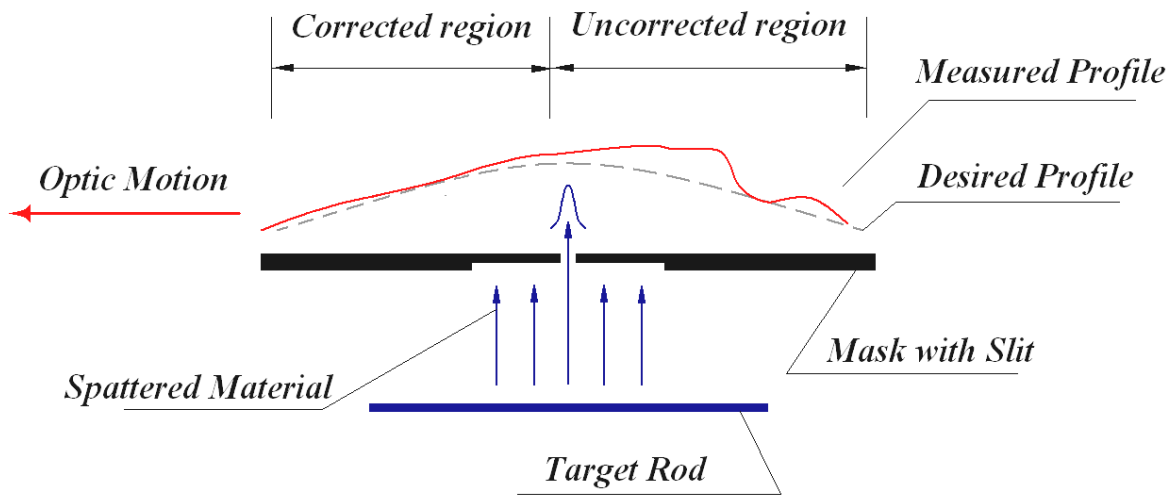


Figure 2. Sputtered target material passes through slit and is deposited on the optic.

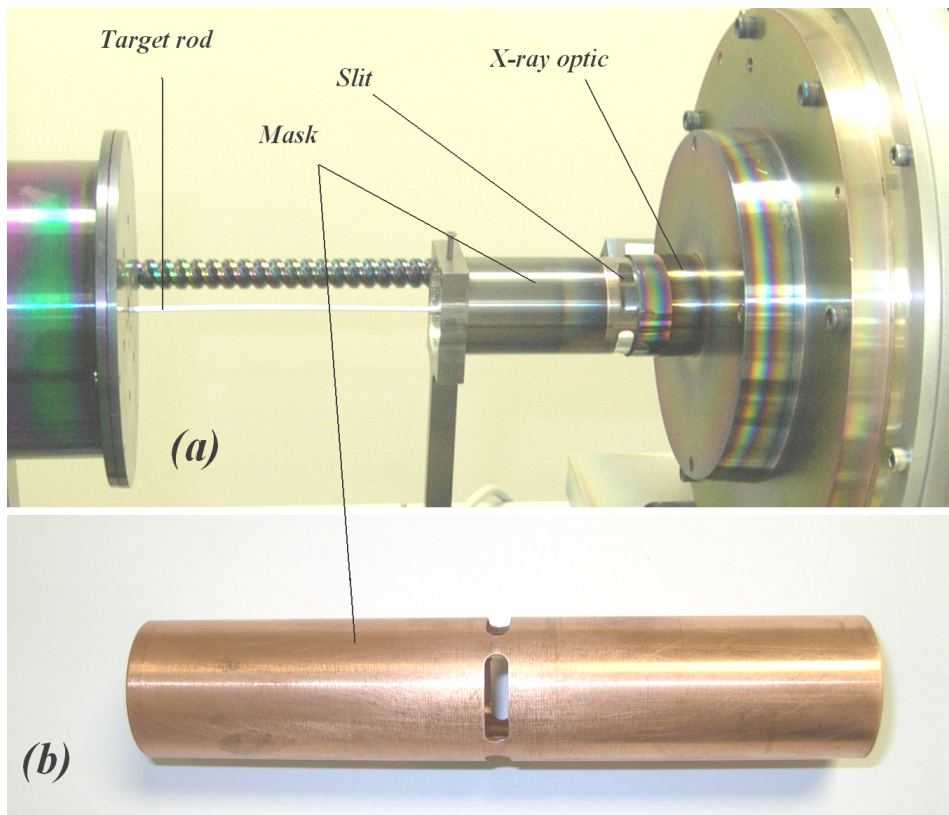


Figure 3. Pictures of (a) experimental set-up, (b) mask with 5-mm-wide slit.

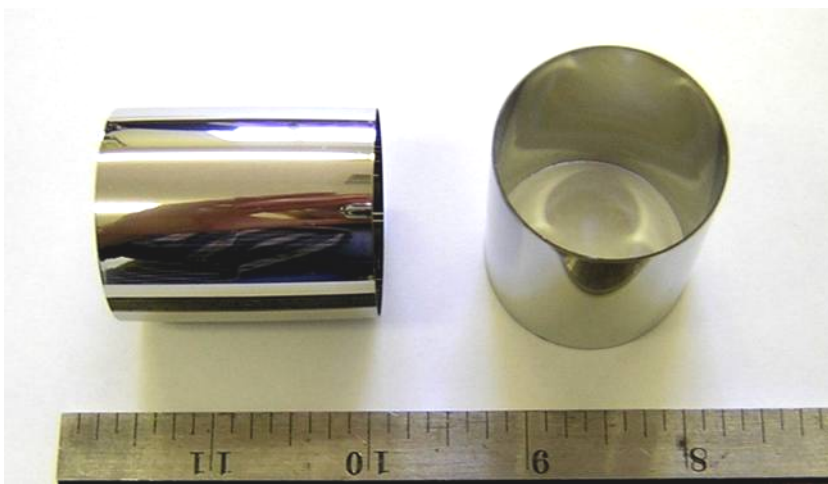


Figure 4. X-ray optics for small animal radionuclide imaging (scale in inches).

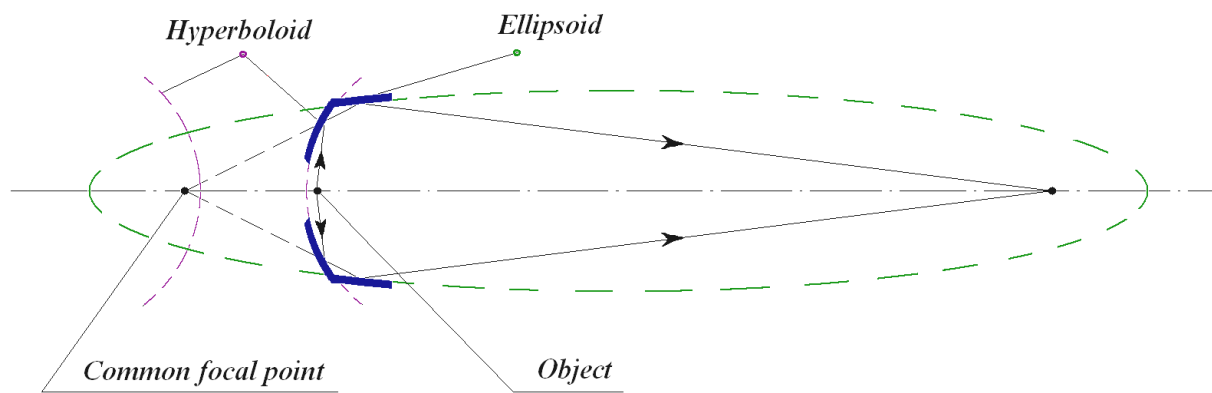


Figure 5. Confocal hyperbola and ellipse geometry.

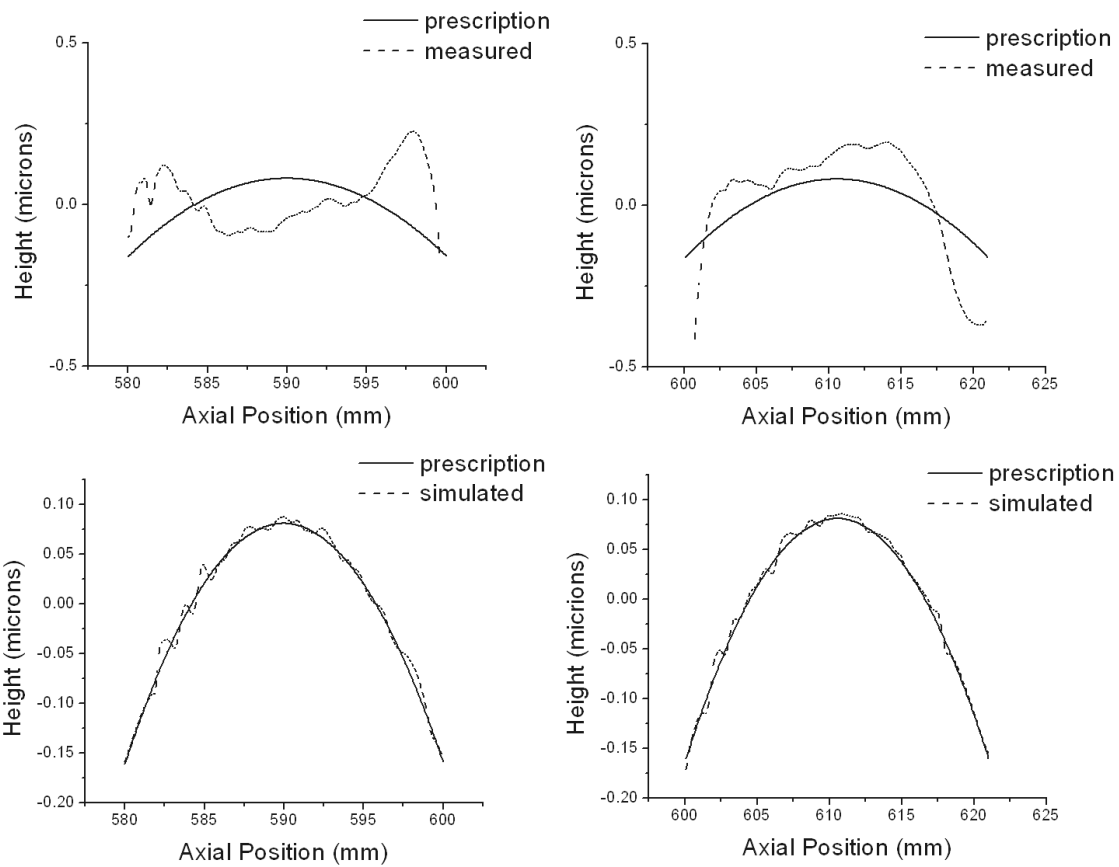


Figure 6. Hyperbola (left) and ellipse (right) profiles before (top) and after (bottom) s series of corrections using 5, 2, 1 mm slits successively.

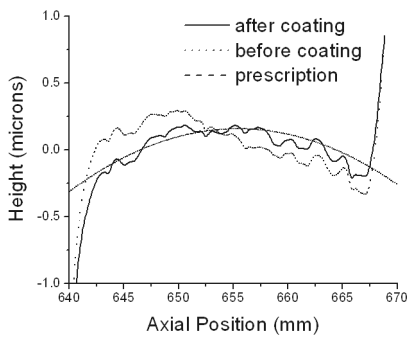


Figure 7. Mirror shell profile before and after correction.

Table 1: Deposition results for various materials and parameters. Bolded values are the chosen combination for differential coating.

	Platinum-Xenon			Platinum-Argon		
Power, W	Pressure, mTorr	Roughness, Å	Deposition rate, Å/sec	Pressure, mTorr	Roughness, Å	Deposition rate, Å/sec
75	15	1.950	0.130	15	2.060	0.140
90	15	2.043	0.230	15	1.933	0.190
75	30	1.895	0.170	30	1.868	0.160
90	30	1.810	0.250	30	2.083	0.220
	Nickel-Xenon			Nickel-Argon		
Power, W	Pressure, mTorr	Roughness, Å	Deposition rate, Å/sec	Pressure, mTorr	Roughness, Å	Deposition rate, Å/sec
75	15	1.915	0.290	15	1.995	0.180
90	15	2.070	0.360	15	1.778	0.240
75	30	3.093	0.240	30	2.260	0.220
90	30	3.630	0.310	30	2.210	0.290
	Tungsten-Xenon			Tungsten-Argon		
Power, W	Pressure, mTorr	Roughness, Å	Deposition rate, Å/sec	Pressure, mTorr	Roughness, Å	Deposition rate, Å/sec
75	15	1.965	0.300	15	1.900	0.120
75	30	1.805	0.290	30	2.125	0.290
90	30	1.993	0.370	30	-	-
75	50	2.075	0.290	50	1.998	0.310
90	50	2.423	0.370	50	1.868	0.370
